Properties of High Intensity Radiation Plasma Sources

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S.V. Parotkin, A.Y. Krukovskiy, V.G. Novikov

Nano-UV sas
EPPRA sas
KIAM RAS
UCD

fire
Fluid, Ions and Radiation Ensemble in Integrated Plasma Modelling

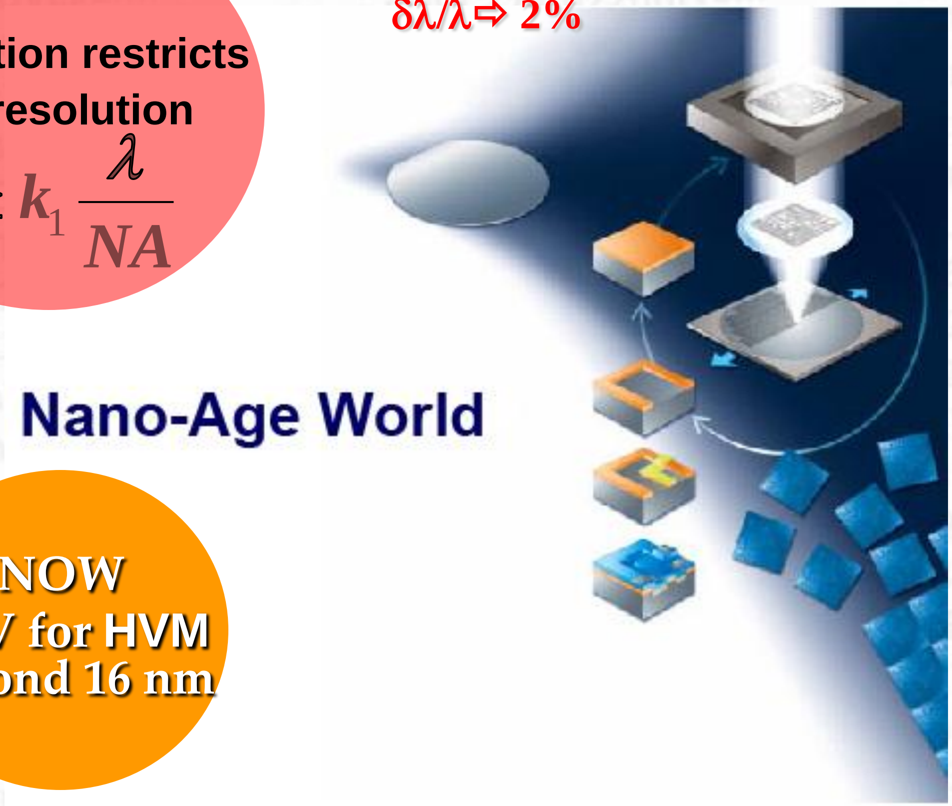
EUV Sources for EUV Lithography

Diffraction restricts the resolution

$$r \geq k_1 \frac{\lambda}{NA}$$

$\lambda \Rightarrow$ 13.5nm ($h\nu$=92eV) $\Rightarrow$ 6.Xnm?

$\delta\lambda/\lambda \Rightarrow$ 2%



NOW
EUV for HVM beyond 16 nm

- For HVM: > 200 W of in-band power @ IF within < 3mm^{2}sr etendue
- For mask inspections ABI$\rightarrow$AIMS$\rightarrow$APMI : 30 $\rightarrow$ >100 W/mm$^2\cdot$sr

Sn, Xe… high energy density plasma (T_e=20-40eV) radiates at EUV range

LPP & DPP can produce a HED plasma

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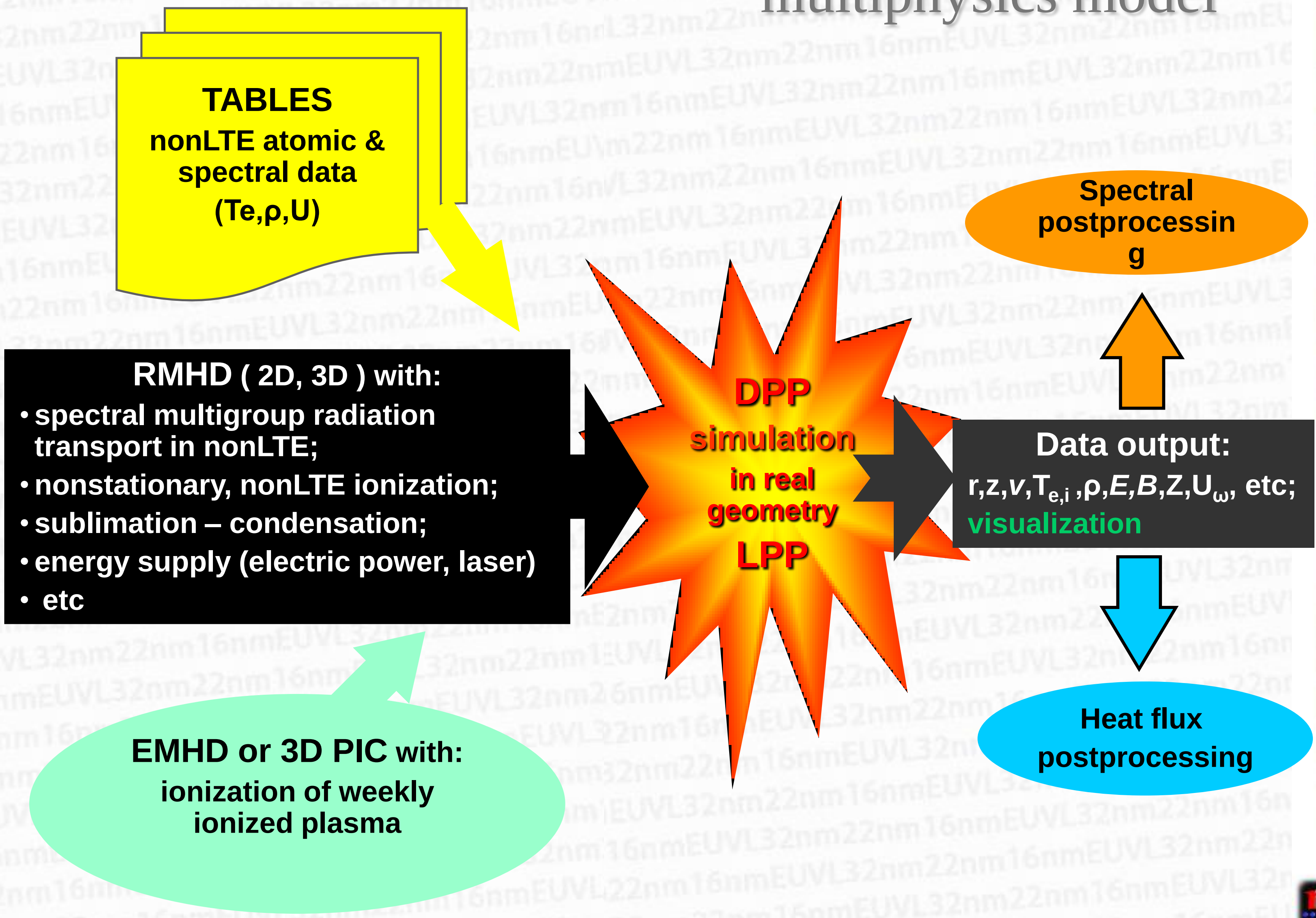
Research Program

- Fundamental understanding on HEDP and radiation plasma sources
- Numerical codes and computational environment development
- Modelling and benchmarking on radiation sources
- Conversion efficiency optimization
- Parametric scans
- Comparison with experimental data and feedbacks

ZETA → Z* RMHD Code → Z* BME → Z+ multiphysics model



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Z* Black-box Modeling Engine

Black-box Modelling Engine (Z*BME) is integrated into a specific computation environment to provide a turn-key simulation instrument, which does not require knowledge of numerical computation.

It has been adapted to simulate DPP and LPP radiation sources in a realistic geometry.

Z*BME has been installed:

in EUVA, Japan

in University College Dublin, Ireland

in Czech Technology University, Prague

A number of joint simulations of EUV radiation sources with Z* -code of Cymer, Bochum University, Xtreme Tech, FOM, EUVA, UCD, Bruker has been performed in frameworks of collaborations and FACADIX, MoreMoore, Medea+, FIRE projects

Next Generation Modelling Tools
- knowledge transfer FP7 IAPP project FIRE

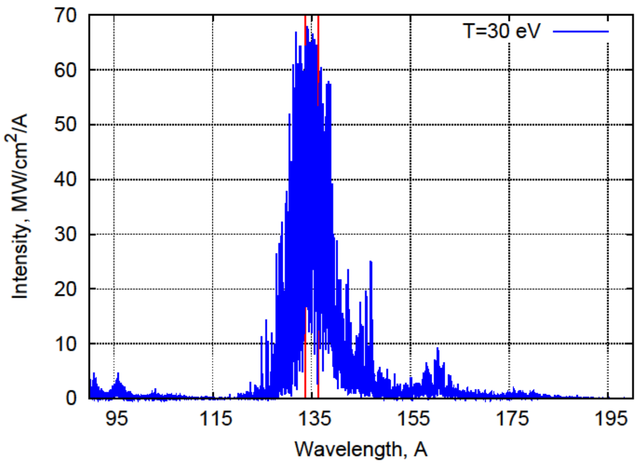
• FIRE - European FP7 Industry-Academia Partnerships and Pathways project

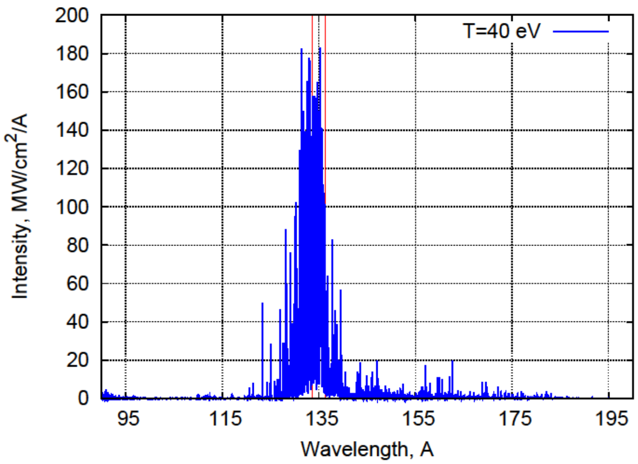
• The FIRE project aims to substantially redevelop the EPPRA's Z* code to include improved atomic physics models and full 3-D plasma simulation of

- ✓ plasma dynamics
- ✓ spectral radiation transport
- ✓ non-equilibrium atomic kinetics with fast electrons
- ✓ transport of fast ions/electrons
- ✓ condensation, nucleation and transport nanosize particles.

• Modelling is essential in parametric scans in EUVL source optimization, in fast particles and debris generation to solve current EUVL source problems as well as extending their application.

EUV Brightness Limit of a Source



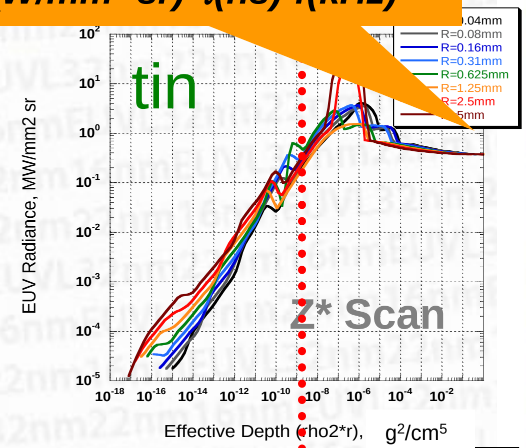


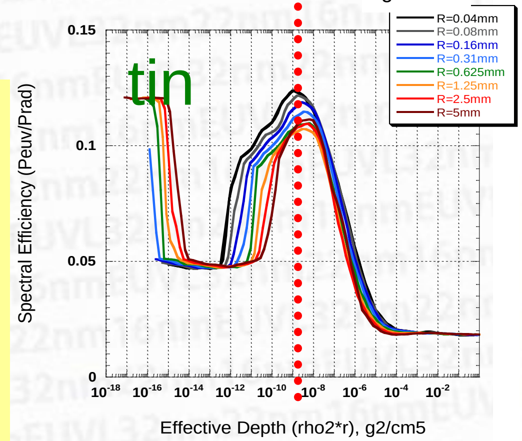
Detailed spectra from tin plasma with radius R=100 μm and $n_e=10^{19}$ cm^{-3}

Spherical model of tin plasma EUV source

The radiation self-absorption limits the in-band EUV radiance from the plasma, and the etendue constraint limits the usable power at IF of a conventional single unit EUV source

$L \approx 1.1(W/mm^2\ sr) \cdot \tau(ns) \cdot f(kHz)$





RMHD scan for tin plasma optimized by radius, temperature and density [AL10]

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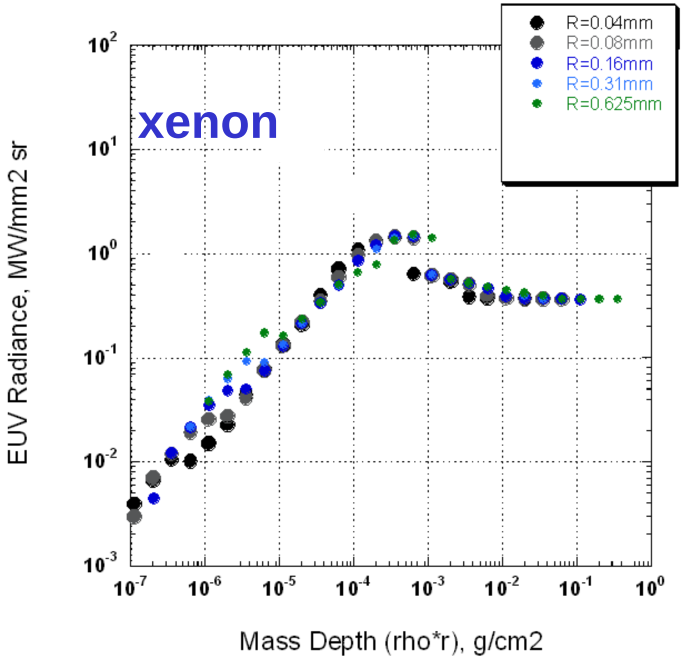
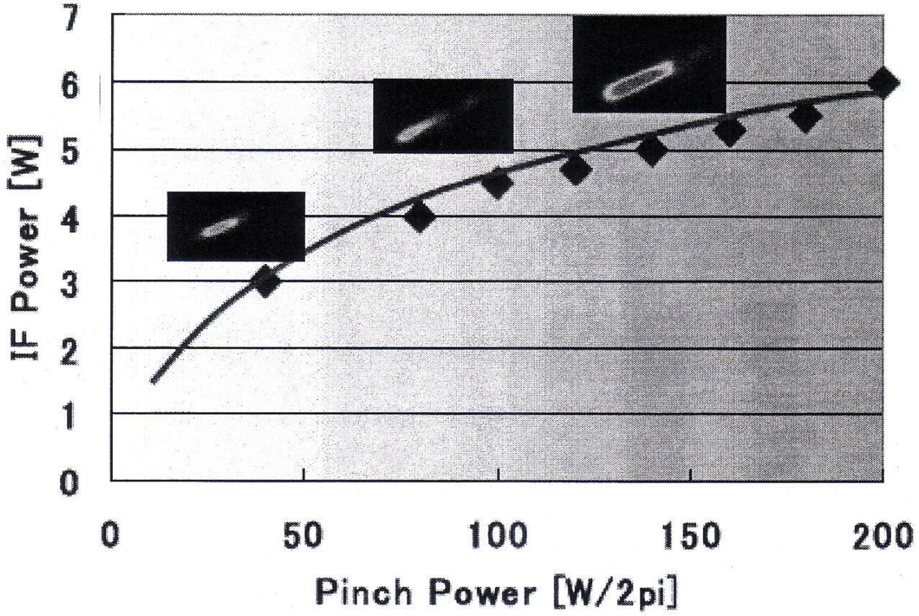
EUV IF Power Limitation:
prediction vs. observation

- Low temperature Xenon plasma EUV emission



Xenon plasma parameter scan with Z*-code showing the in-band radiance limitation from XeI-XeXI ions



Experimental observation of limitation of the in-band EUV power at IF from xenon DPP source

[M. Yoshioka et al. Alternative Litho. Tech. Proc. of SPIE, vol. 7271 727109-1 (2009)]

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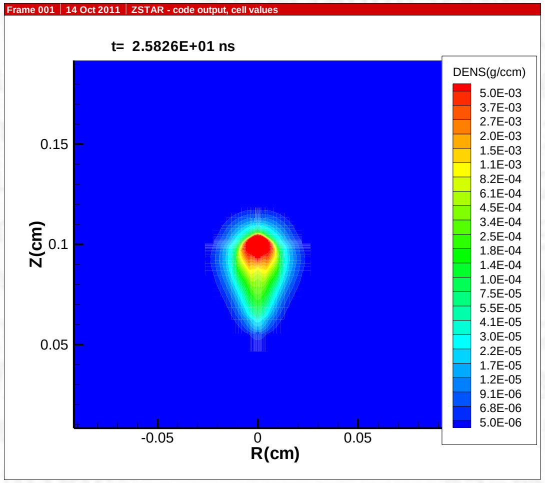
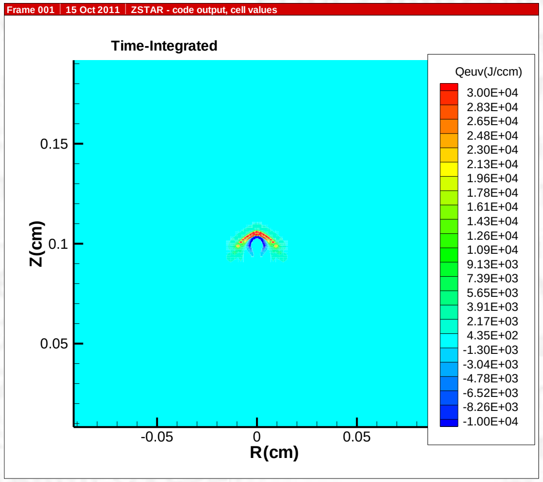
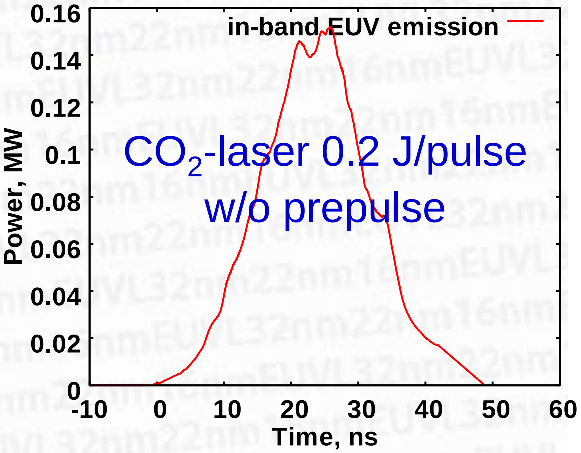
LPP EUV Source

under CO_2- laser or combined pulse



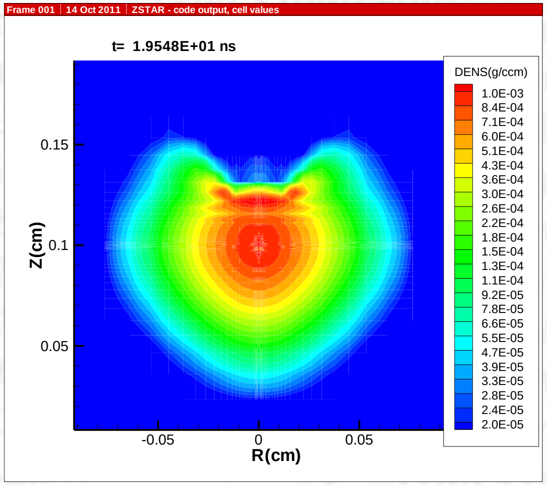


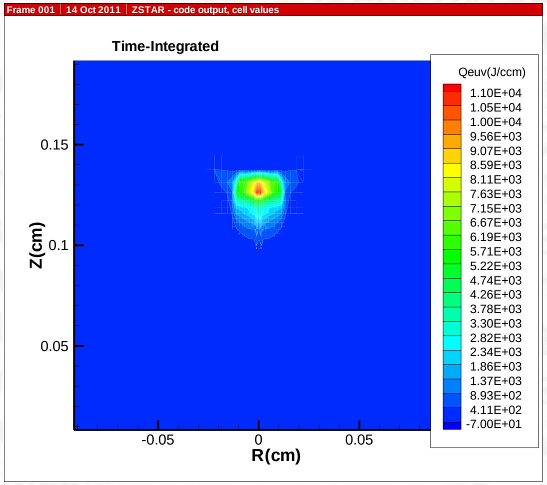


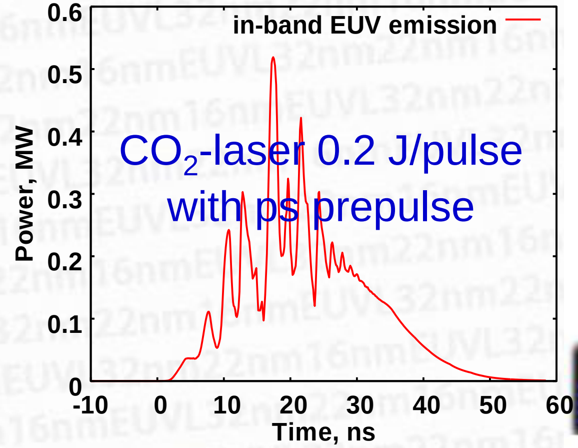
Tin plasma density at EUV maximum

Time-integrated EUV source image (cross-section)

The maximum EUV brightness is up to 15 W/mm^2 sr kHz







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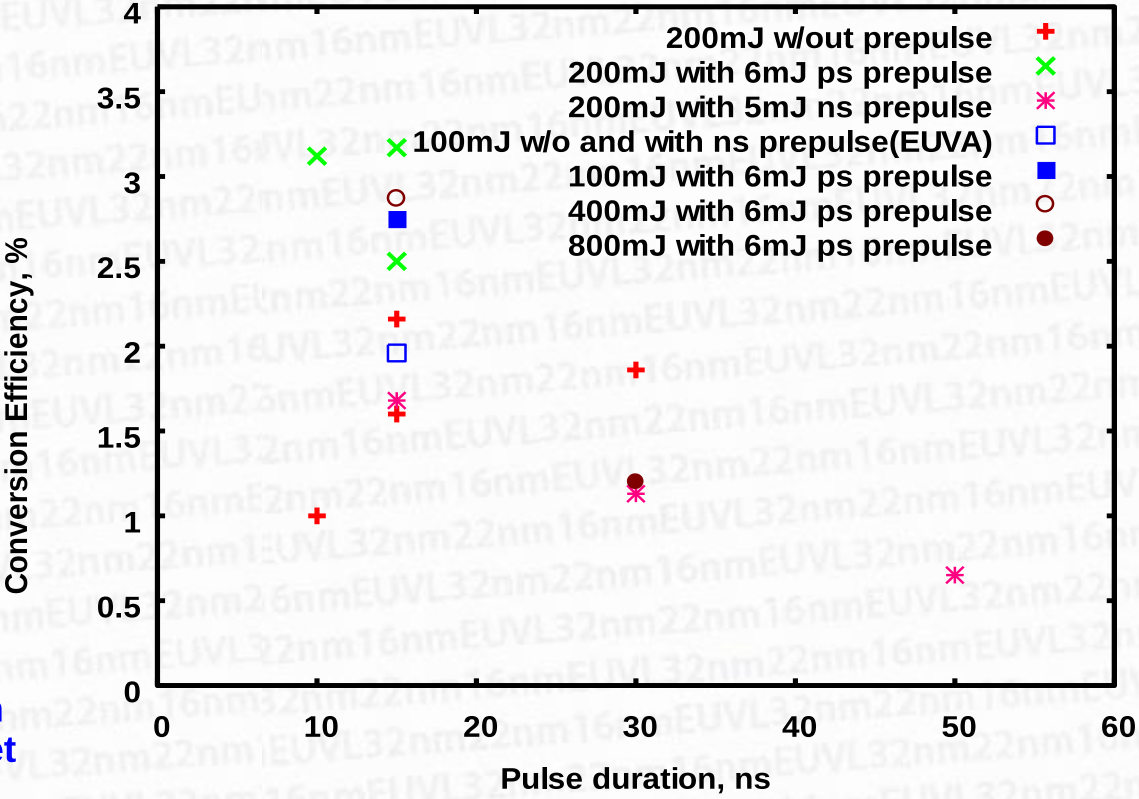
Conversion Efficiency of CO_2-laser
on pulse duration, with & w/out pre-pulses

Main pulse: CO_2-laser 0.1-0.8 J/pulse, 10,15,30,50ns fwhm, 200μm focal spot
Pre-pulse laser (if applied): Nd:YAG 5 mJ 1-10ns pulse, 40μm spot size
or Nd:YAG 6 mJ 10-100 ps pulse, 40μm spot size

Target:
Liquid tin droplet of 40μm diameter
or
20μm for 100mJ (EUVA)

Conditions:
different focal positions;
different time delay between pre- & main-pulse

CE depends strongly on laser intensity and target irradiation conditions



CE maximum of 3% can be reached at high laser energy (200mJ) in combined ps-ns pulse

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Nano-UV: High Brightness EUV Source

micro-plasma-pulsed discharge

Power source

Charge energy	0.2 – 0.5 J
Current	5 - 10 kA
Pulse	~10-20 ns
Capillary dimension:	∅ 1.6 mm L = 12-18 mm

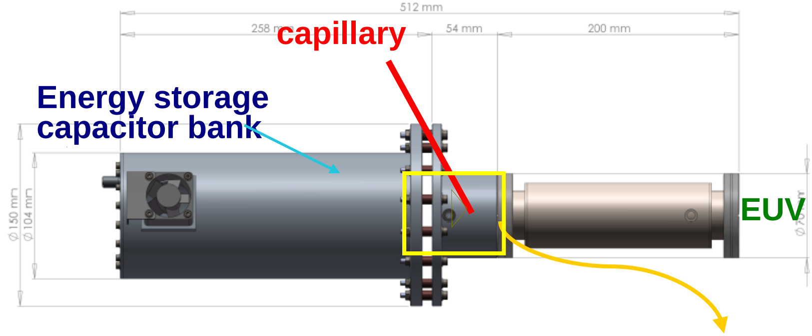
Various electrode geometries

Gas:

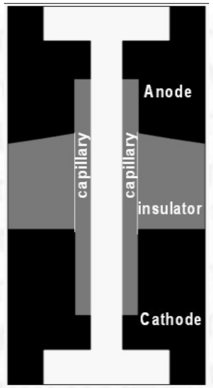
0.02-2Torr gradient He;

Xe, N_2, Ar, Kr,, … admixtures

(for narrow-band radiation source)



Experimental set up



Example of simulated geometry

Capillary discharge dynamics & emission features:

E-beam, plasma channelling (ε>>1)

Volumetric MHD compression (skin depth >>plasma diameter)

Highly ionized ions (fast electrons)

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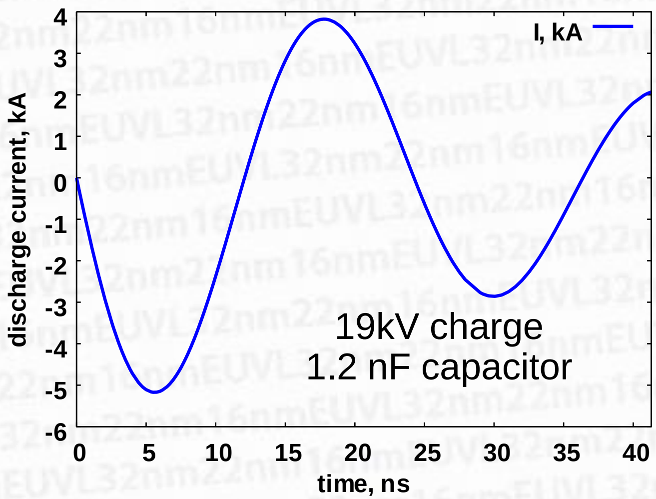
MPP Discharge EUV Source

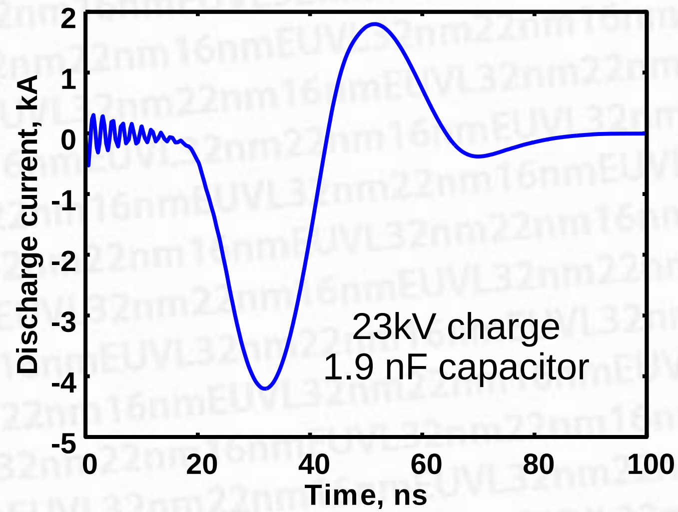
resistive regime

Inductive regime



Nitrogen – buffer gaz

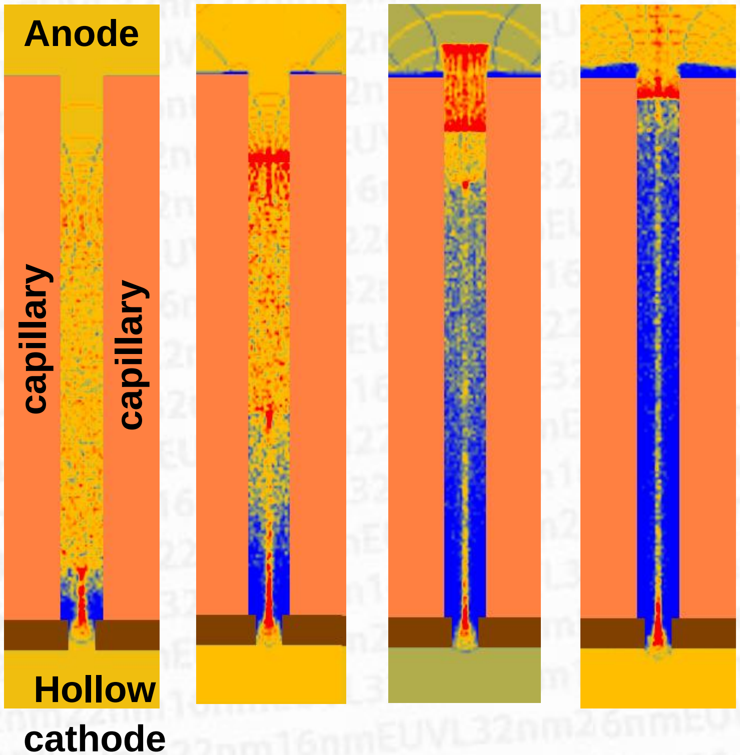
Resistive regime



In a resistive regime of capillary discharge, the high joule dissipation in the tight conductive channel produced by hollow cathode electron beam creates an efficient mechanism of plasma heating and EUV or soft X-ray emission consequently.

Also, fast electrons increase the ionization degree of heavy ion (Xe,…) plasma increasing eo ipso EUV yield.

MPP Discharge EUV Source
- fast electrons 3D-PIC modelling



Electron beam in the HC capillary discharge

⇒ run-away electrons

⇒ electric field drops deeper into HC

⇒ e-beam concentration (ε >>1)

⇒ e-beam-gas ionization

⇒ ionization wave

In the first few nanoseconds, run-away electrons from the hollow cathode generate a tight ionized channel (< 200μm diameter) in the gas

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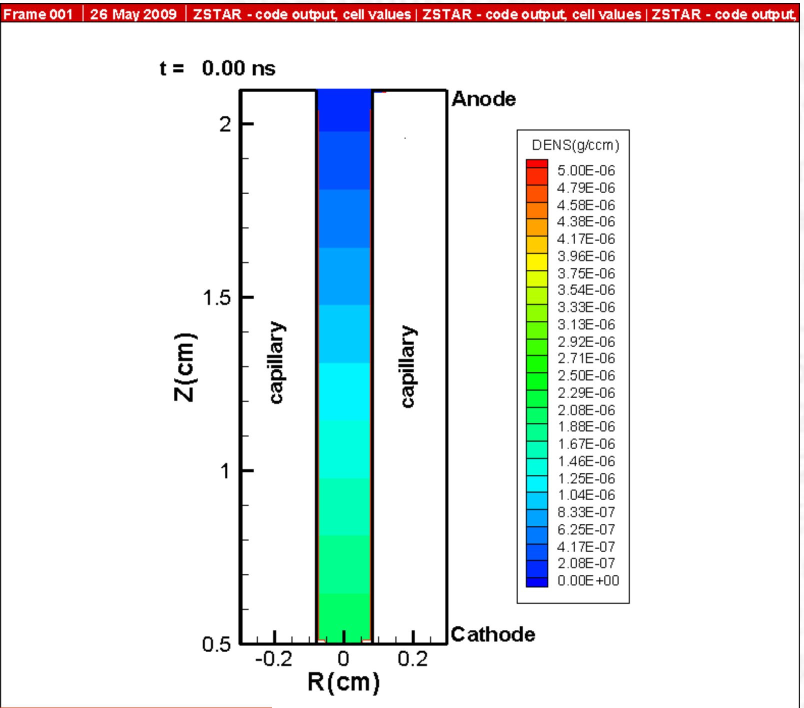
MPP Discharge EUV Source

dynamics & EUV emission



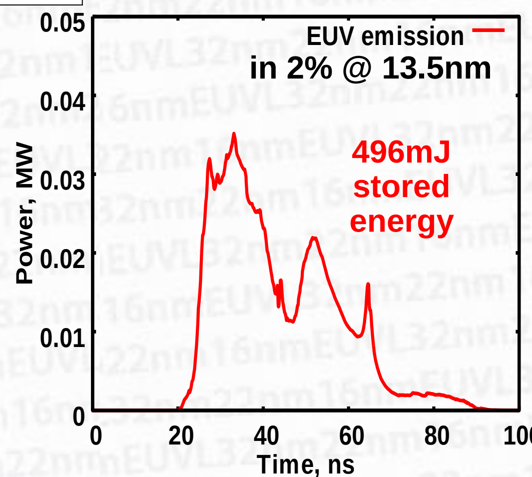
3D volumetric compression

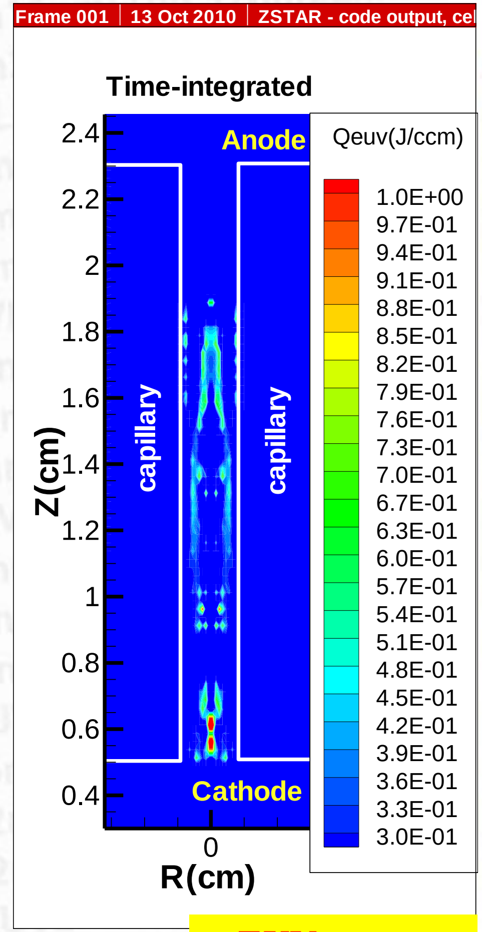
N_e=2-3 $\cdot 10^{17}$cm^{-3}, T_e=25-40eV.

Calculated in-band EUV emission from the system is of 0.885 W/kHz

The traced along the axis the system EUV intensity @ 13.5nm wavelength is of

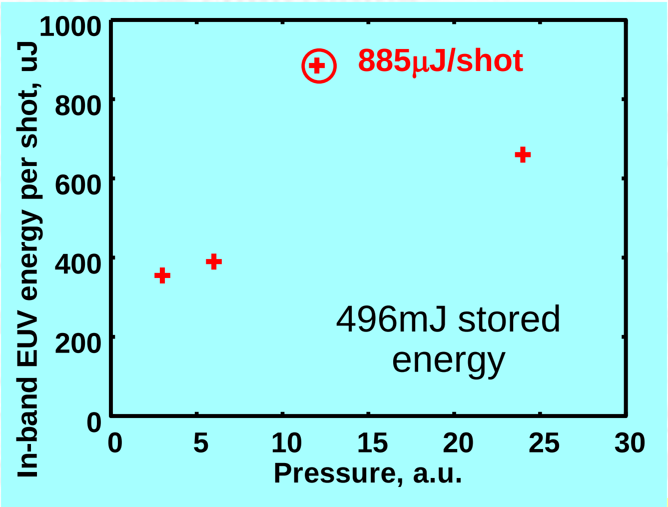
15.3 W/eV mm^2 sr per kHz





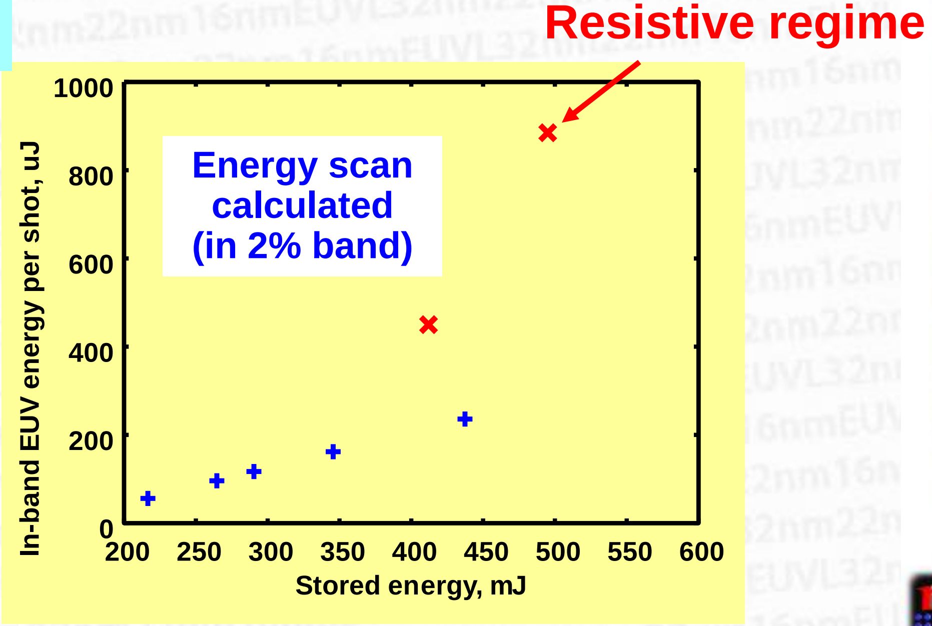
EUV source cross-section

MPP EUV Source
- characteristics & optimization from Z* modelling



Optimization by gas mixture pressure

EUV source scan by stored electrical energy



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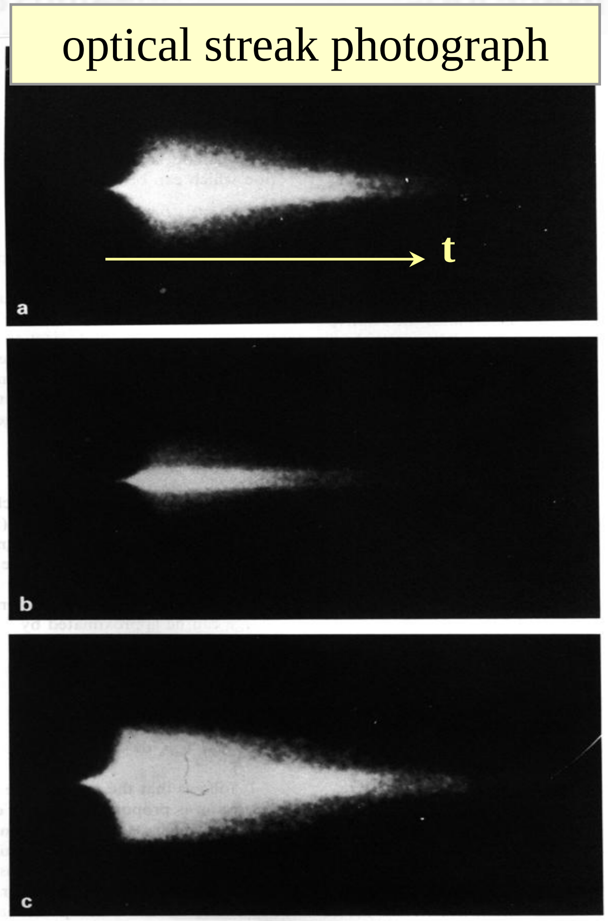
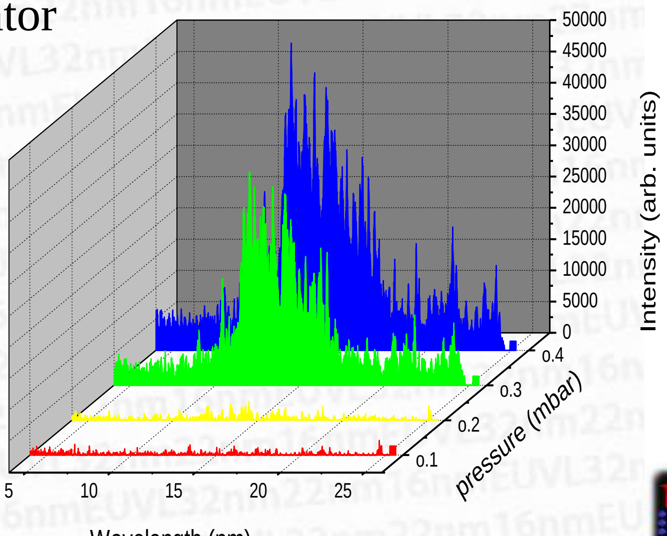
MPP Discharge Experiment

- plasma discharge emission from a channel produced by hollow cathode electrons

optical streak photograph



- pulse charged local energy storage
- sub-mm diameter capillary
- hollow cathode e-beam for on-axis discharge initiation
- rapid current heating
- ultra-bright high energy density radiator



- 1st EUVL Symposium, Dallas 2002 -

European Pulsed Power Research Applications

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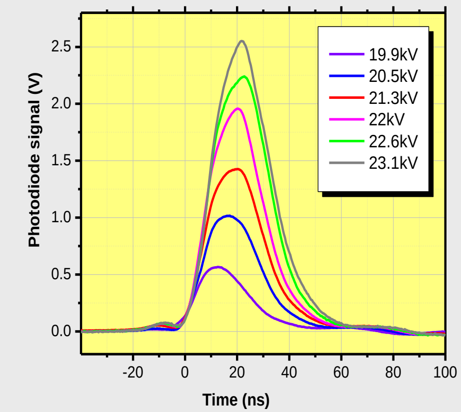
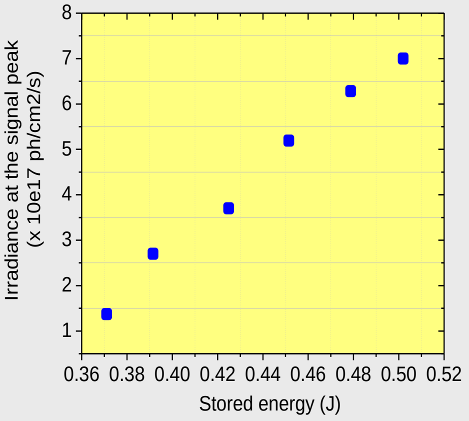
Progress in experiment

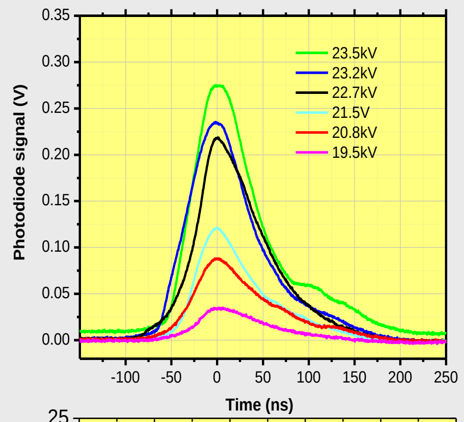
- irradiance vs stored energy

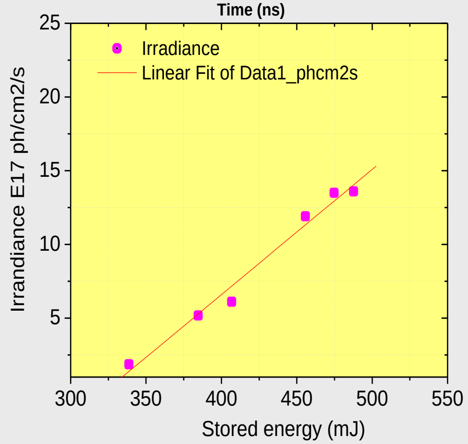
Results presented at EUVL october 2010

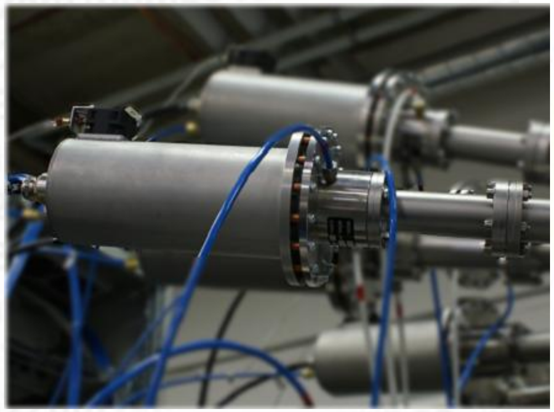




<u>Current Results</u>







At same operating voltage

- ✓ **Improvement on the fuel gas mix and flow rate**
- ✓ **2 fold increase in the irradiance**
- ✓ **3 fold increase on power**

Scaling to higher power demonstrated with Sn admixture

more details at experimental talk (S43): P.Choi, V.S. Zakharov et al

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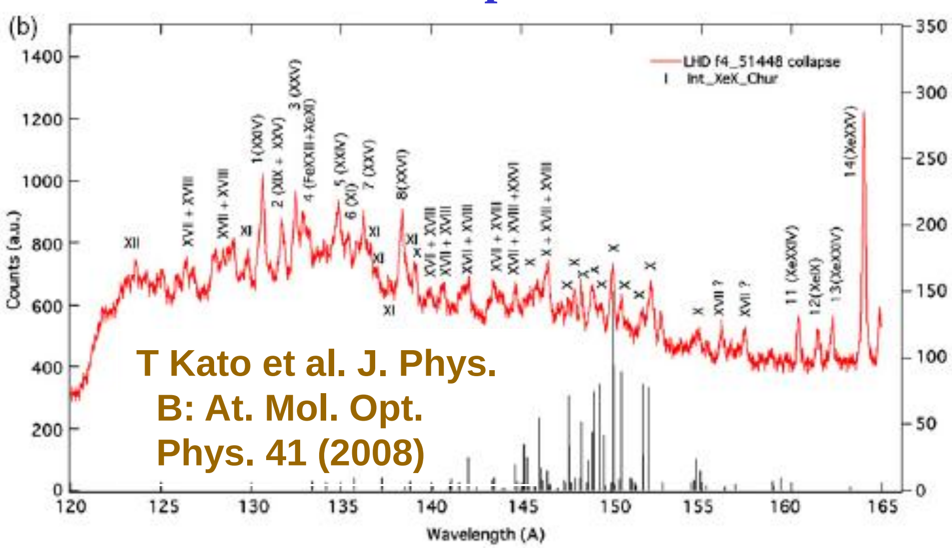
Bright EUV Emission

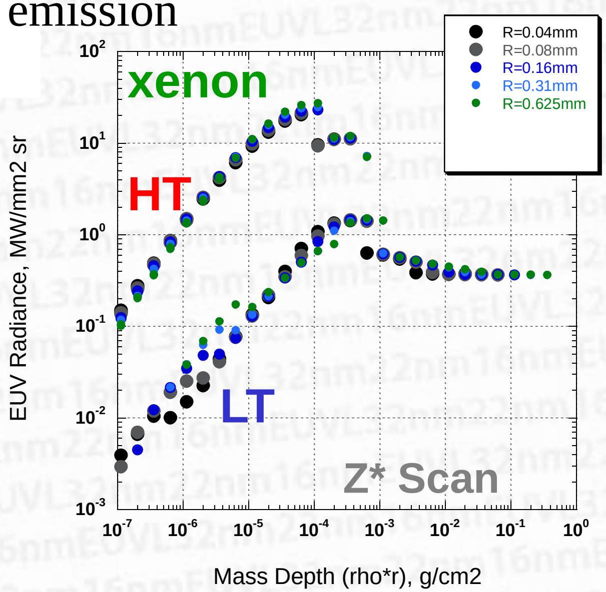
from highly charged xenon ions

Tokamak experimental data



T Kato et al. J. Phys. B: At. Mol. Opt. Phys. 41 (2008)

- There are two regimes in transparent plasma of xenon: Low - Temperature (LT) with XeXI and High - Temperature (HT) with XeXVII-XeXXX ions contributing into 2% bandwidth at 13.5nm.
- For small size xenon plasma, the maximum EUV radiance in the HT can exceed the tin plasma emission



- **XeXXII - XeXXX** produce bright 4f-4d*, 4d-4p*, 5p-4d* [White, O'Sulivan] ($3d^n4f^1 + 3d^n4p^1 \rightarrow 3d^n4d^1$) satellites in EUV range near 13.5nm
- **XeXXII** has ionization potential 619eV

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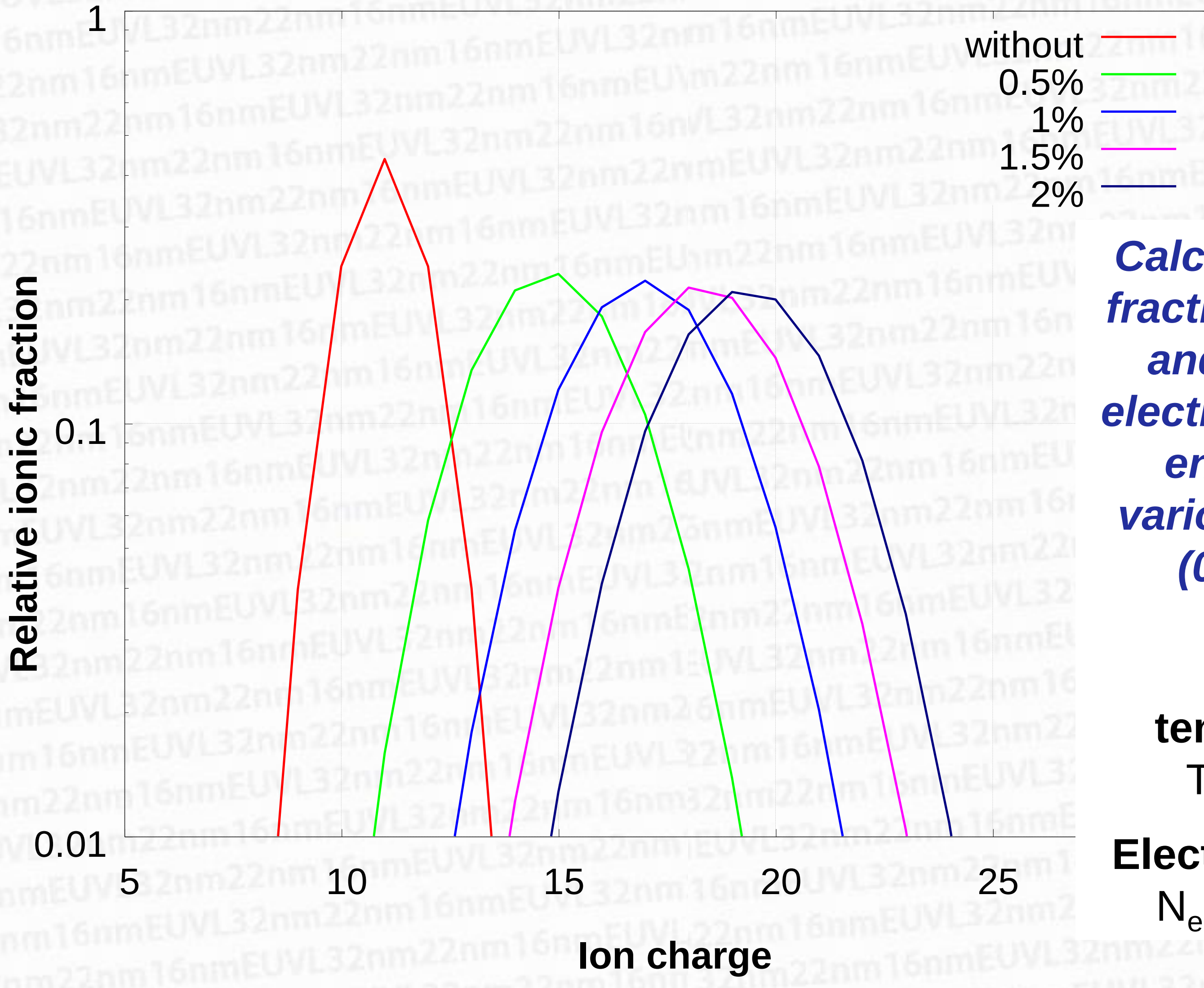
High Degree Xenon Ionization

- in plasma with fast electrons



Calculated ionic fractions without and with fast electrons of 5keV energy and various fraction (0.5%-2%)

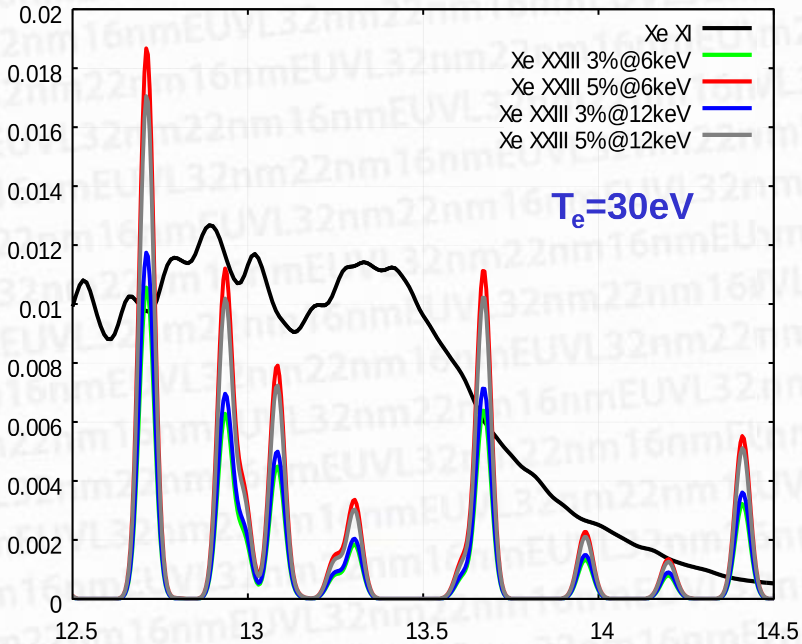
Plasma temperature

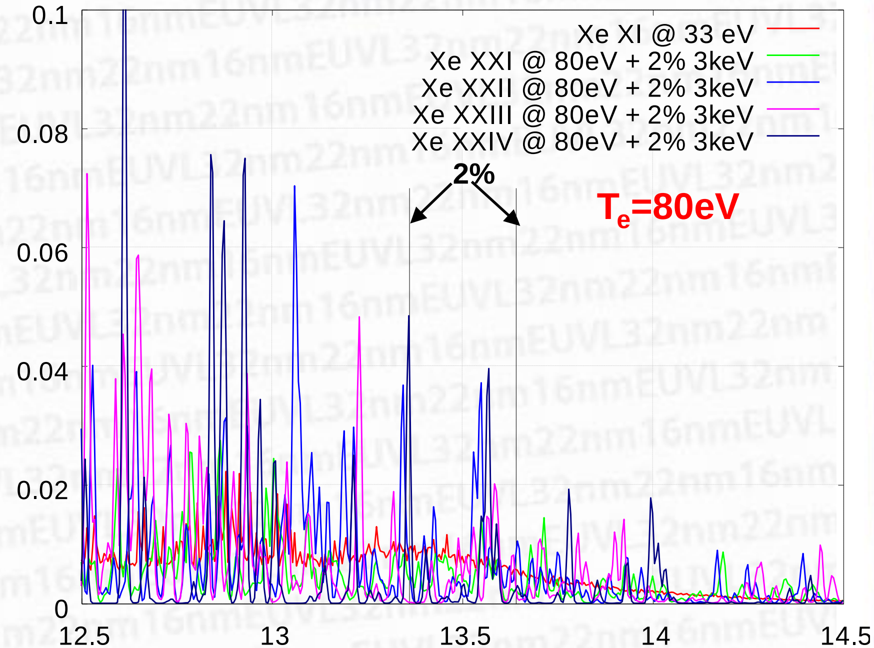
T = 40 eV

Electron density

$N_e=10^{17}$ cm^{-3}

EUV Emission of Highly Charged Xe Ions
- from plasma with fast electrons





To produce the maximum EUV light power the double condition is required:
+ fast electrons have the energy of few keV to produce the highly charged ions
+ plasma has the temperature sufficient for the excitation of required transitions

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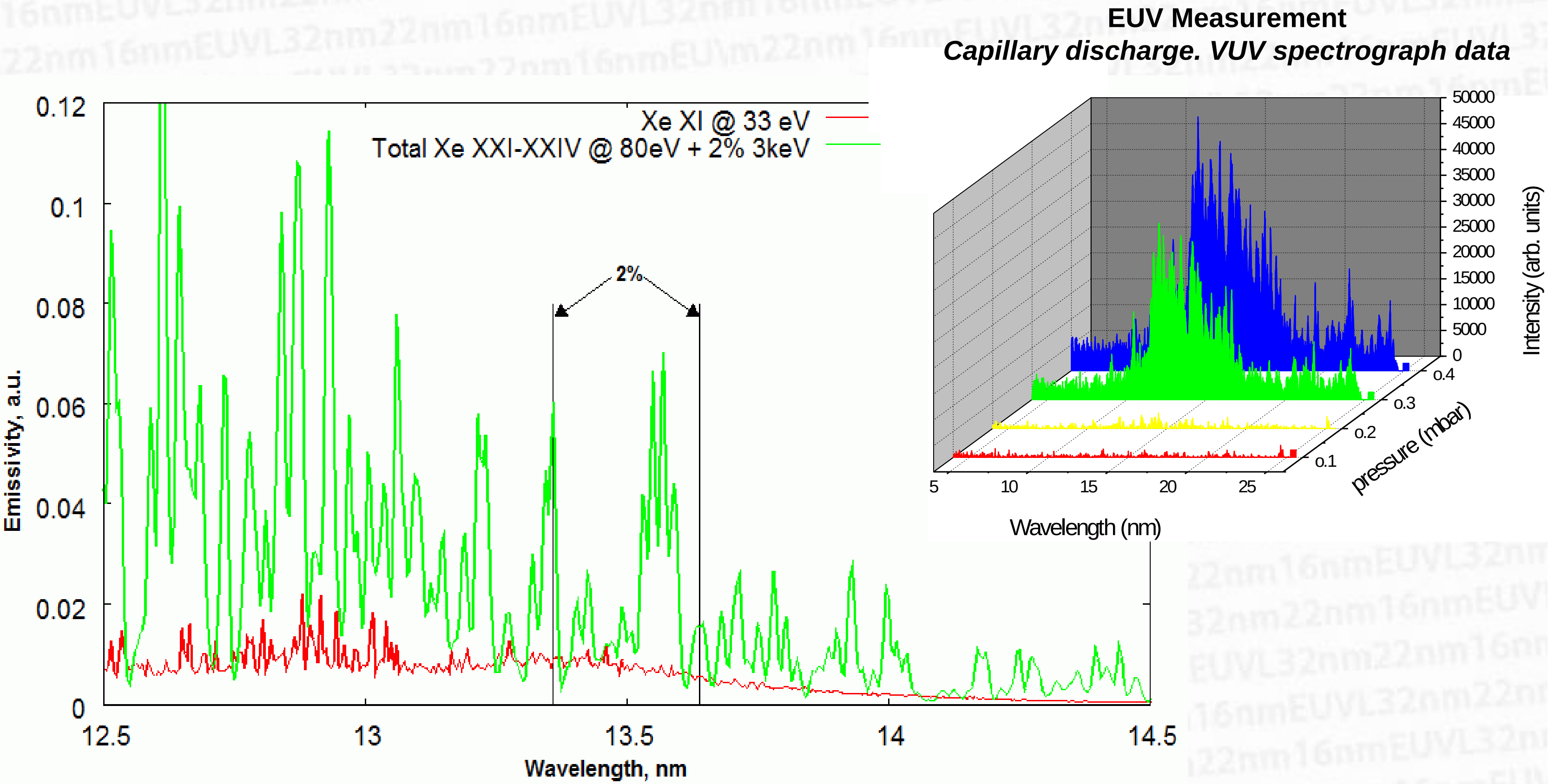
EUV Emission of Highly Charged Xe Ions
- from e-beam triggered discharge plasma



Bright EUV emission in 2% band at 13.5 nm can be achieved from highly charged xenon ions in plasma with small percentage of fast electrons

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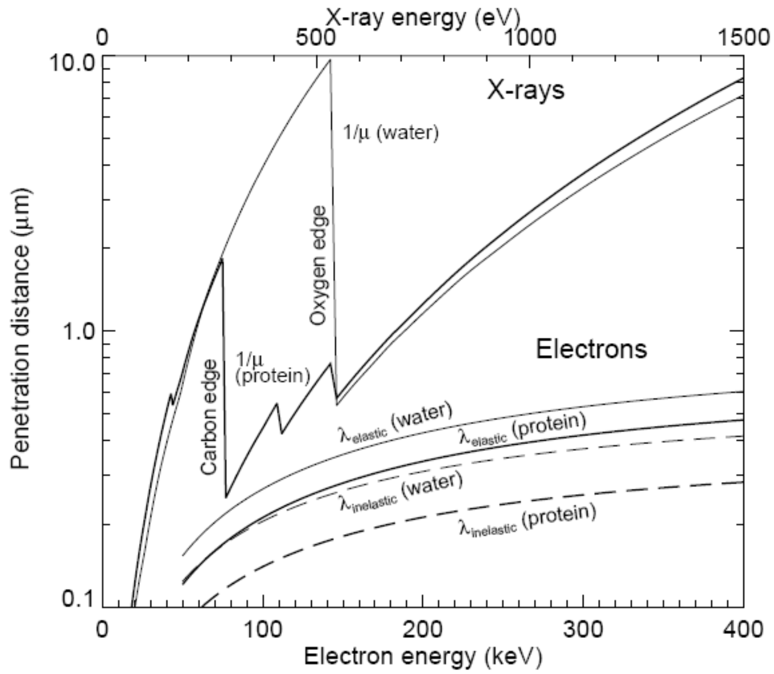
Soft X-ray Microscopy

deep penetration & high contrast



Penetration distances in water and protein for electrons and X-rays

Soft X-ray microscopes and their biological applications
Janos Kirz, Chris Jacobsen & Malcolm Howells
- Q. Rev. Biophys. 28, 33{130 (1995)

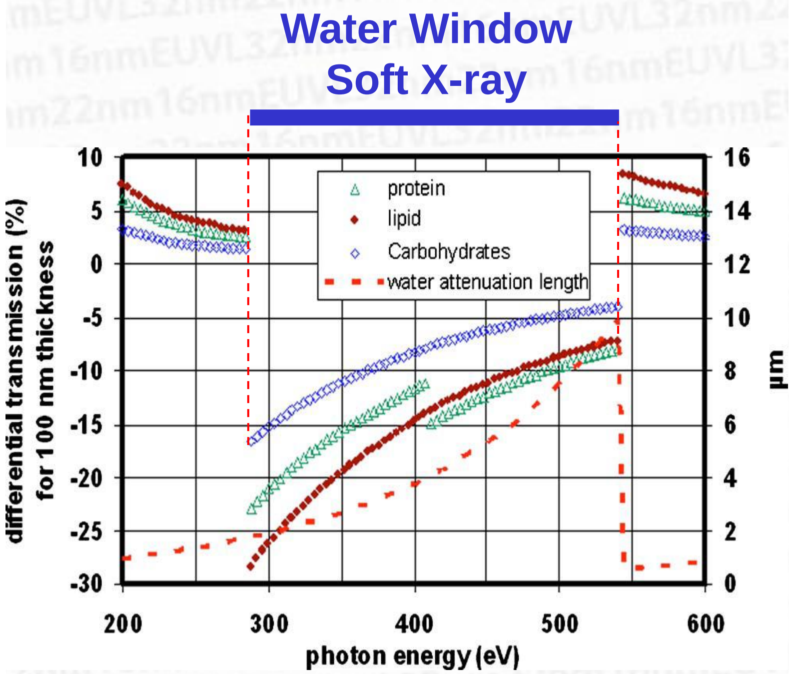


Table-top water window transmission x-ray microscopy: Review of the key issues, and conceptual design of an instrument for biology.
Jean-François Adam and Jean-Pierre Moya, Jean Susini- Rev. Sci. Instrum. 76, 091301 2005

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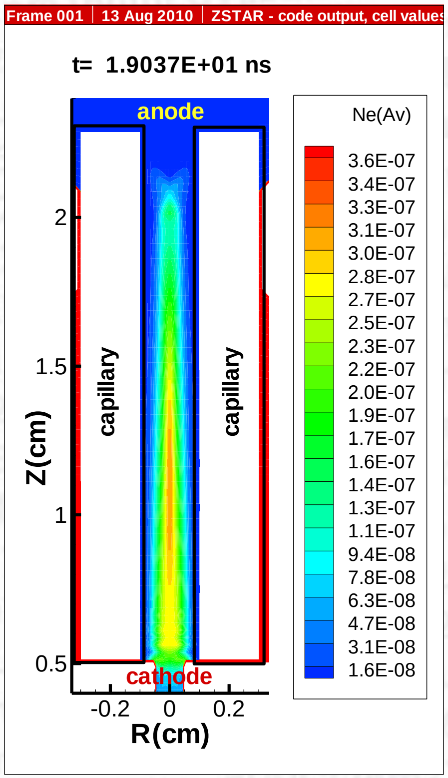
MPP source for soft x-ray microscopy

Z*-code modelling

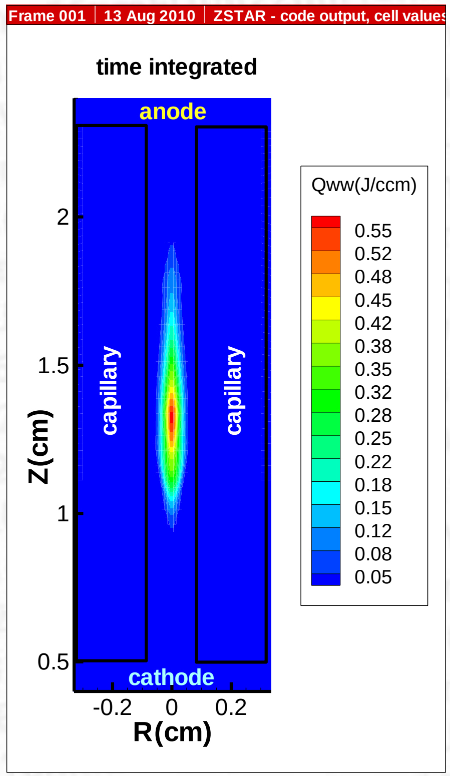
Nitrogen plasma near emission maximum



0.48J/pulse charge

Fast electrons induce discharge in 3-D volumetric compression regime

Time integrated image of soft x-ray (426.5 - 431eV) source

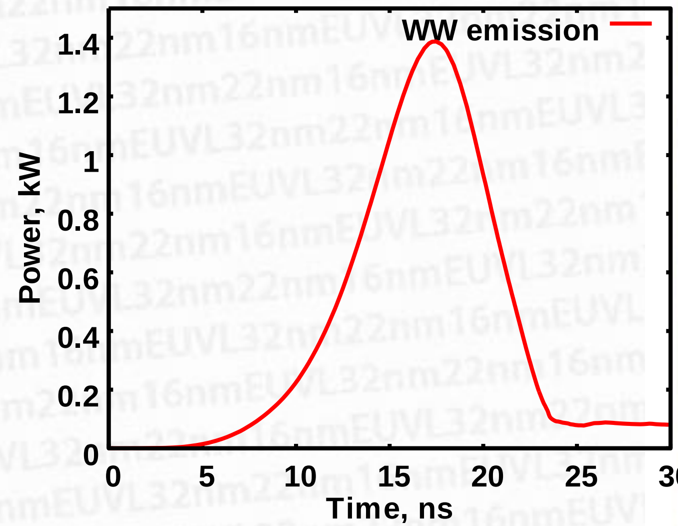


$\langle Z \rangle \approx 4\text{-}5$

$T_e = 45 - 55\text{eV}$

$n_e \approx 2{\cdot}10^{17}\text{cm}^{-3}$

Soft x-ray pulse in 0.01nm band @ 2.8817nm



Nitrogen: He-like and H-like

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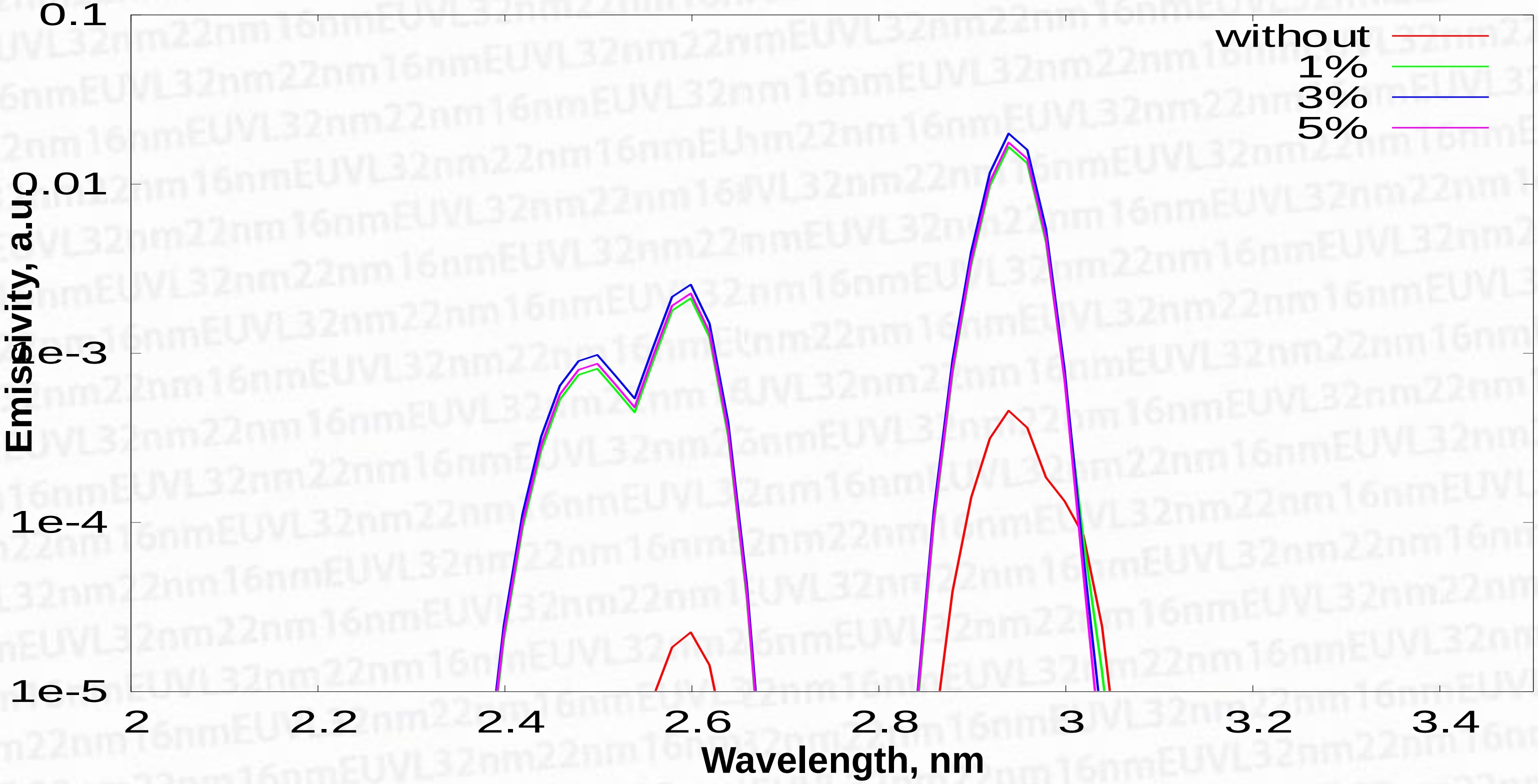
Fast Electrons

enhance soft X-ray radiance of nitrogen plasma

- Non-equilibrium plasma kinetics



Line emission spectra of Nitrogen from non-equilibrium plasma at T=45 eV with various portions (1% to 5%) of fast electrons with 5 keV energy in comparison with emission spectrum of equilibrium plasma at the same temperature. Electron density $n_e = 10^{17}$ cm^{-3}.

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  - Keldysh Institute of Applied Mathematics RAS, Moscow, Russia
  - University College Dublin
  - EUVA, Manda Hiratsuka, Japan
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